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# Evaluation method of GNSS-based positioning functions for safety applications in operational conditions

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**Abstract**

Most of the positioning functions in railways today rely on track side sensors that are efficient, but offer mainly discrete positioning, lead to high maintenance costs and differ between countries. Railways demonstrate their interest for the localization technology based on GNSS. Use of the satellite technology for safety operations is a major possibility. The condition is to evaluate the positioning function in terms of the RAMS attributes, as required by railway standards. However, no current evaluation methods are able to consider the signal degradations of wireless communications caused by the railway environment. We propose, in this paper, a methodology based on an Operational Experience Feedback procedure for quantifying RAMS properties and their sensibility to the operational conditions. The applications will focus on the Tr@in-MD project devoted to dangerous good tracking. Scenarios, i.e. temporal sequences constituted of up and down states that succeed randomly, will help to provide the results. To obtain different scenarios of evolution, the Ergospace software will be used. Raw data associated to a wagon that runs on an itinerary in different typical railway environments, with different satellite configurations, will be collected and processed.



*Keywords:* GNSS-based localization; railway applications; certification; RAMS

## 1. Introduction

Satellite-based localization technologies are strategic opportunities in railway applications because they offer new possibilities of service and have advantages that current technologies, relying mainly on

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infrastructures deployed along track, cannot equal. On the one hand, they can complement or replace the trackside equipment and thus, reduce the installations and consequently the associated costs. On the other hand, they can contribute to improve railway network capacity as they provide train positions rather than track section occupancies. GNSS (Global Navigation Satellite System) can, in particular, offer localization services in ERTMS (European Rail Traffic Management System), the system developed to harmonize, at European scale, railway signalling and control/command systems. However, using GNSS in such safety applications is slowed down when trying to comply with railway standards. Indeed, demonstrations of RAMS (Reliability, Availability, Maintainability and Safety) properties are required on new solutions embedded in trains (EN 50126 2000). They aim at verifying if all dependability (RAM) and safety aspects are controlled over the lifecycle of the solutions before using them operationally. To analyse the localization service delivered by GNSS, the RAMS evaluation techniques are not able to consider the signal degradations, and in particular those provoked by environment effects. These one are caused by signal reflexions on obstacles like vegetation or railway cuttings. As the position calculation is based on signal propagation time measurement from the satellites to the user reception antenna, any signal delay is susceptible to degrade the service.

The main challenge is so to develop proof methods capable to be applied to any technical architectures based on GNSS, consistent with the railway certification process dedicated to safety-related systems and, able to consider signal degradations. In this article, we will focus on what can bring GNSS alone for railway safety applications given constraining railway environments for signal reception. To contribute to this effort, we propose a methodology that evaluates several RAMS properties of a GNSS receiver by analysing the localization data provided in output of the receiver. Thus the environment, source of numerous localization errors, can be considered when the measurements are obtained from a receiver embedded in a train evolving in a railway context. The methodology uses a specific *Operational Experience Feedback* procedure that will be described in the third section of the article. In particular, we will detail the type of RAMS properties that can be obtained. Before, the second section will present why the research projects working on the utilisation of GNSS focus today on railway safety applications. We will take the case of the Tr@in-MD project devoted to dangerous good tracking, for which we worked to obtain RAMS values given different environments configurations. The final section will present these results. We have used GPS localization data coming from simulations in order to control the environment configuration with 3D models. We will detail the processing of the data following the proposed procedure and we will make a synthesis of the obtained results.

## 2. Satellite technologies for railway localization

### *2.1. Toward the utilization of GNSS in railway safety applications*

The use of GNSS in railway transportation is considered as an interesting alternative to current localization systems as they allow activities related to the logistics of freight transportation to be improved and the trackside equipment to be reduced. The utilization of satellite technologies in the railway sector is, today in Europe, limited to non-safety-related applications. Indeed, having very low risks, these applications are more easily accepted and put into service than those having an impact on the safety of individuals and goods. Although there is some reticence to use GNSS for railway safety applications, some groups of researchers and industrialists have proposed test systems on the last ten years, in order to take an active part of the ERTMS standard that concerns the European harmonization of railway signalling. Indeed, the satellite technologies can bring an efficient and interoperable answer to fill the gap between the ERTMS concept of self-sustaining vehicle localization and its implementation. In the projects conducted until now (such as Integrail, Gaderos, Locoprol) (Gu 2005) (Bustamante et al. 2003)

(Simsky et al.2004), two different design approaches have been considered for the localization solution: either GNSS is the main part of the solution or is used in combination with additional technologies (e.g. inertial platform, digital information on track topography, train-communication network). The design strategy has been oriented towards the standalone or hybrid GNSS solution according to the intended goal, principally: reduce costs of development / material / installation / maintenance or improve accuracy / availability / continuity / integrity performances. For example, a low cost solution is privileged for the train operation on rural railway lines that are often unprofitable because of the low density traffic, in contrast with high speed lines for which high performances are demanded.

New systems intended to play a role in the control and command of trains have to be realized "in safety", as it is the case for the today existing infrastructures (EN 50129 2003). This means that the systems have to be designed either using fail-safe principles, i.e. the system have to be able to enter or remain in a safe state when a failure occurs, or using a high level of safety when a risk-based principles is employed. However, to reach this goal, industries need to know what to do in terms of standardization and certification of GNSS equipment, especially concerning RAMS evaluation, to provide the proofs that can lead to the approval of the product by railway safety authorities.

In the following, we will focus on the French Tr@in-MD project, where only GPS is used to localize freight wagons. The first objective in this project was not to develop a safety-related system "in safety" but to obtain a high reliability of the system parts: a geo-localization, a communication, and a detection parts that examine wagons and their hazardous goods (see below). We worked in this project to analyse the performances of the geo-localization service given the surrounding environment of the receiver. This research work has led us to develop a RAMS methodology described in the third part of the paper, methodology that can serve in other projects.

### *2.2. Satellite localization in the Tr@in-MD project*

The objective of the Tr@in-MD project (Transport intelligent par fer des Marchandises Dangereuses – intelligent railway transportation of hazardous materials) is to develop a system that can supervise the transportation of dangerous goods like chemicals, acids, gas, explosives, etc. and that can detect and inform of incidents using intelligent sensors (cf. Fig. 1 that gives an example of the wagon instrumentation). A single wagon that carries hazardous goods can be part of different trains between the departure and arrival points, can be stopped (in a marshalling yard, a freight station...) and parked at shippers or consignees plants, so the logistics chain is complex (Minary 2008). The GPS solution has been chosen to localize such single wagons given the capability to track and trace any mobiles by installing compact equipment like beacons on vehicles. Today, in France, the freight locomotives (about 2000) have been equipped with GPS to track freight trains and inform clients; the wagons are not equipped.

The application of GNSS in Tr@in-MD is safety-related as any problem concerning the transportation of hazardous goods (leakage of chemicals, over pressure in tank, etc) can potentially lead to risky situation for the surrounding environment and the population. So, high performances are required for the system, in particular, the reliability and the availability of the localization service. The procedure proposed hereafter makes possible to evaluate RAMS properties. We will focus only on the two first criteria whose values are expected in the project. The assumptions used to establish the procedure will be detailed beforehand.

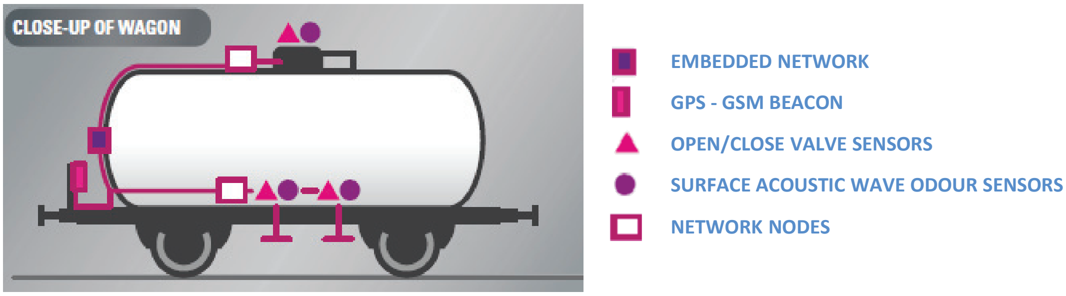


Fig. 1. Example of embedded instrumentation of a wagon in the Tr@in-MD project

## 3. Procedure based on experiments for the evaluation of RAMS

### *3.1. Assumptions*

From the railway users' point of view, only the quality of the localization function provided in output of the GNSS receiver is important. This quality depends on how the GNSS sub-systems (satellites, ground stations and the user receiver) realise their mission. Specific requirements exist to define the quality level a user can expect from the global satellite system. However they do not encompass the uncontrolled errors in the signals caused by the local environment of propagation, even if characterizing them is fundamental for safety applications. The work presented hereafter will focus on these local phenomena to investigate the research issue related to the evaluation of the RAMS properties of a wagon localization unit. Thus, we will assume later in the article that problems occurring in the equipment placed before the GPS receiver (interruptions or faults in the transmitted signals) are controlled as well as the software and hardware failures in receiver.

To consider now the influence of the environment along the wagon routes, it is obviously impossible to describe a limited number of representative geometries of the environment mask. However, with the objective to evaluate RAMS properties, we have studied environment configurations that have identical geometry features along the wagon itinerary. The area around this itinerary constitutes actually a "typical" environment. RAMS results can then give representative characteristics for different typical environments observed. It is consequently possible to make comparisons between different environment properties. We will consider also that the receiver is placed at the top of a wagon to avoid the masking effect of the vehicle on the satellite signals.

Our evaluation procedure based on GNSS measurements captured in conditions of operation is now described. How the collected data are managed to determine probabilities or average values is presented after having detailed the states of the localization function we analyse.

### *3.2. The proposed evaluation procedure*

#### *3.2.1. States of the localization function*

We identified three states for the output function of the receiver that is "to deliver estimated positions". Figure 2 represents them and an illustration of a train associated to a correct and a wrong localization.

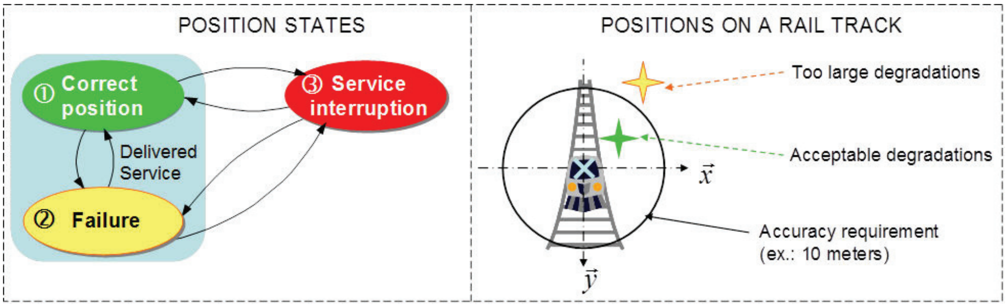


Fig. 2. State of the position delivered by the localization function

The three states are:

1) correctly estimated position, i.e. when the true position, unknown for the receiver, is inside a circle centred on the position calculated by the system. The circle radius is equal to the maximum position error tolerated by the user and corresponds therefore to the accuracy requirement.

2) incorrectly estimated position, i.e. when the estimated position is outside accuracy boundaries. In this case, there is a failure of the function but, as this is not recognized by the system, the localization service is still delivered.

3) the position is not delivered because, at the receiver level, number of signals received are insufficient. In this case, the localization service expected by the user is interrupted.

The RAMS evaluations concentrate on the hazardous states 2 and 3.

### *3.2.2. Principles of the procedure*

We use an Operational Experience Feedback (OEF) methodology to obtain an efficient procedure capable of managing a huge quantity of data in order to evaluate RAMS properties. This approach follows usual steps that we have here adapted to the GNSS localization.

In an OEF analysis, collected data can give information on the system behaviour and its evolution in relation to the period of operation (Lannoy 2002). These data can be facts or events like incidents, failures, degradations, maintenance operations, during the given mission time of the system. They are processed and analysed subsequently.

Data associated to real positioning measurements in railway environments can be recorded to keep trace of the operational behaviour of the GNSS receiver. What can be collected are events and not failures (see state 2 of figure 2) as they cannot be identified during measurements. These data provide, more precisely, information associated to signals – intrinsic properties or satellite/receiver path characteristics – and also information associated to signal processing leading to position estimations. They could serve to identify failures a posteriori. To determine accuracy of an estimated position, a reference is needed. Existing technical solutions can give very accurate reference (for instance, an inertial platform composed of several sensors embedded in train). The proposed procedure begins with the data collection and continues with several processing steps:

- In the first step, a selection is carried out from the amount of collected data stemming from receiver output files. Indeed, even if these files are organized according to a given format (in RINEX or NMEA format for instance), the inside data are very heterogeneous. We can find, for example, satellite coordinates, ephemeris, signal to noise ratios, geometrical quality criterion, pseudo-ranges errors (the satellite/receiver distances estimated by the receiver) and their variance. They constitute raw data that are unworkable for a RAMS evaluation. Useful data leading to the position estimation are extracted at each sampling instant.

- In the second step, the useful data are processed to obtain information related to correct and hazardous states (Beugin 2009). To determine if there is a failure or not, each position has to be compared with the true position (the reference).
- Finally, the obtained information leads to quantitative values that can be subsequently analysed statistically in order to get RAMS results.

The results are in relation with the considered accuracy requirement because it serves to determine whether positions are correct for users or not. This requirement can be very constraining (ex.: 1m) or more supple (ex.: 100m). So, the procedure can lead to different results that depend on a requirement.

### *3.3. The evaluated RAMS properties*

The information obtained in the last step of the procedure can lead to average values, probabilities or distributions that can serve for the RAMS evaluation. Table 1 presents characteristics that can be obtained concerning reliability and availability criteria, those that we quantify in the framework of the Tr@in-MD project. The table also explains how they can be calculated. The [1)] refers to the quantities that are used and [2)] refers to the process leading to the specific properties.

Up time and down time are concepts that appear in Table 1. The up time for the localization function is a sub-part of the whole receiver utilisation time that only includes periods when the function is in correct operation. The down time only includes periods when the function is in down states caused by failures and service interruptions.

To apply the proposed approach, our measurements will be obtained using simulations in artificial environments rather than using a receiver placed in real operational conditions. This can seem contradictory to OEF analysis that relies, by definition, on real data. But, in so doing, we first aim at showing the feasibility of the method and to make it possible to compare typical environment characteristics. Moreover, with a simulation, the exact trajectory of the mobile is known. In practice, this information can only be obtained with the deployment of an expensive solution. The results obtained using different railway environments are presented below.

Table 1. RAMS properties obtained after calculation

| **Average values** | | |
|---|---|---|
| MUT | Mean Up Time | 1) Periods of correct operation without interruption<br>2) Average on all period lengths |
| MDT | Mean Down Time | 1) Periods of service delivered incorrectly (failure or interruption)<br>2) Average on all period lengths |
| Average frequency of incorrect positions | | 1) Number of failures or service interruptions on a given period<br>2) Average on the number of all sampling instants |
| **Probabilities** | | |
| Instantaneous availability | | 1) Position state at each sampling instant<br>2) Average on the number of operational scenarios |
| Average availability | | 1) Sampling instant with correct operation<br>2) Average on the number of all sampling instants |

## 4. Application of the approach and results

### *4.1. Simulation of railway conditions*

The Ergospace software is employed for the simulations. This tool uses 3D numerical models of environments (called scenes) in which a mobile can circulate. It provides pseudo-range values associated to each satellite of the GNSS constellation. Signals that can reach the mobile are determined using a 3D ray-tracing principle. Errors due to local propagation phenomena are calculated by applying optical geometrics laws and ray tracing techniques.

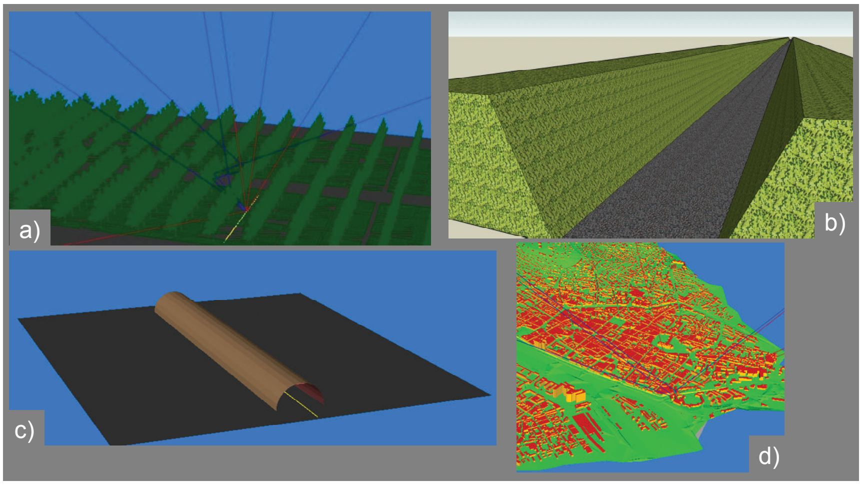


Fig. 3. (a) Wooded environment; (b) Railway cutting environment; (c) Tunnel environment; (d) Urban environment

We have selected four typical railway environments. The 3D models of these environments are illustrated in Fig 3: a) the wooded environment (Trees have been regularly placed to facilitate the model construction), b) the railway cutting environment, c) the tunnel environment (A tunnel totally masks the signal reception. The interest is the signal propagation effects at the tunnel entrance and exit.), d) the urban environment (The model of the city of Rouen is used; it integrates buildings without architectural details).

In a scene linked to a model, the wagon route appears in yellow, direct rays in red and reflected rays in blue (see sub-figure a).

### *4.2. Use of scenarios for statistical evaluations*

The procedure is based on measurements that are captured in conditions of operation and that are processed statistically. Basically, acquisitions have to be performed during a long period of observation to obtain significant amounts of data. As data come from simulations rather than real measurements, a wagon itinerary is restricted to the simulation software limits. Consequently, the observation period can only be short. Nevertheless, to apply this approach, we use scenarios. One scenario is a sequence constituted of a succession of states associated to the localization function. To obtain different scenarios with the Ergospace software, raw data are collected as follows: the run of a wagon equipped with the GPS receiver is simulated at several moments on a given day in order to consider different configurations of the GPS satellite constellation. The wagon runs through the same itinerary with a start at the beginning of each hour. The number of scenarios is established knowing that a satellite configuration for a given place at a given instant will be nearly the same 24 hours later. Thus we consider that one simulation performed each hour on a given day is sufficient and will lead to 24 distinct scenarios. It refers to a wagon that does several round-trips per day.

### *4.3. Results of the approach*

The utilization of the proposed procedure leads to evaluations associated to a given level of accuracy. Levels are different from one railway application to another as different localization performances are expected. To cover a wide range of applications, we have tested three levels of accuracy: 50, 10 and 1 meter.

Table 2. RAMS properties obtained for 4 environments associated to 3 different accuracy level

| **Environment** | **Accuracy** (in m) | **MUT** (in sec) | **MDT** (in sec) | **Availability** (in %) |
|---|---|---|---|---|
| Wooded | 1 | 1.5532 | 30.4886 | 16.35 |
| | 10 | 4.1362 | 8.7554 | 40.59 |
| | 50 | 11.7207 | 4.267 | 60.23 |
| Railway cutting | 1 | 2.2757 | 7.2305 | 37.76 |
| | 10 | 4.6875 | 3.2319 | 65.37 |
| | 50 | 11.4347 | 1.3542 | 87.76 |
| Tunnel | 1 | 1.0208 | 16.5834 | 10.97 |
| | 10 | 1.2708 | 16.4584 | 13.38 |
| | 50 | 1.4792 | 16.0416 | 15.57 |
| Urban | 1 | 3.2626 | 13.6713 | 30.78 |
| | 10 | 4.8916 | 3.3638 | 58.84 |
| | 50 | 27.6458 | 1.0342 | 93.38 |

The results presented in Table 2 show that with the same environmental constraints the MUT values decrease with the growth of accuracy and the MDT values increase with the growth of accuracy. Indeed, the application associated to the most tolerant accuracy requirement will have naturally better results than the others.

The urban environment has the highest MUT (27 seconds) for an accuracy requirement of 50m compared to the other environments. The operating periods become very short as soon as a higher level of accuracy is required (3 to almost 5 seconds). In fact, when a receiver moves in such area, the satellite visibility varies strongly because of the extremely uneven elevation of the architectural elements along the route. Masking effects perturb then the reception of the signals and consequently degrade the accuracy and limit the availability of the service. These results prove that, for the urban environment, the localization function enters frequently in down states for high accuracy levels.

Low MUT values in tunnel are not significant because they only explicit the absence of signal reception in tunnel. Also, the availability is relatively low: the reception is in the mode "all-or-none": either it is available and accurate or totally unavailable. For the other environments, the MDT values logically increase with the growth of accuracy. For an accuracy requirement of 10 m, the MDT and MUT values are equivalent. This proves that, for this 10 m level, the transitions between up and down states vary enormously.

The wooded environment has the highest MDT (30 seconds) for an accuracy level of 1 m because of the variability of the environment.

For the railway cutting, occurrences of down states are frequent as MUT are short but availability is high. This proves in fact that state transitions are multiple.

### *4.4. Synthesis*

The results emphasize that mean up times are greater in environments with varying conditions, like the urban and wooded environments, as opposed to the other environments. The tunnel environment is a specific case. Mean values are not significant because MDT or availability values only rely on the tunnel length. Values that characterize the tunnel entrance and exit are the only ones which are meaningful. They have so to be analyzed instant per instant and not using average values.

In all cases, rapid degradations of quality can be observed when the accuracy requirement increases. Degradations are the greatest for the urban environment.

For a 10 m level, state transitions are most frequent, especially in the railway cutting case.

## 5. Conclusion

In the railway domain, standards are used to control the integration of new equipment in safety applications. The objective is to ensure the adequate safety conditions when using such equipment in the guided transportation system. Even if experiments have shown the applicability of GNSS in the railway domain, the utilization of the different existing (GPS, GLONASS, EGNOS) or future satellite systems (GALILEO) cannot be taken for granted in the applications dedicated to safety. Indeed, analysts, in a certification context, are faced with difficulties to apply the RAMS evaluation techniques recommended by the railway standards to examine RAMS properties of GNSS solutions.

In this article a procedure using data based on experiments was proposed to evaluate RAMS properties. The obtained results in the framework of the Tr@in-MD project showed the impact on the localization function of different railway environments with identical geometry features.

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